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A Sharp Interface Method for Compressible Multi-Phase Flows Based on the Cut Cell and Ghost Fluid Methods

Xiao Bai[1,2] and Xiaolong Deng[2,*]

[1] *School of Mathematical Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China*
[2] *Building 9, East Zone, ZPark II, No. 10 East Xibeiwang Road, Haidian District, Beijing Computational Science Research Center, Beijing 100193, China*

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Abstract. A new sharp interface method with the combination of Ghost Fluid Method (GFM) and Cut Cell scheme is developed to study compressible multi-phase flows with clear interfaces. Straight-line cutting is applied on the cells passed by the interface. A new real-ghost mixing method is presented and applied around the cut cells to deal with very small cut cells. A cut face reconstruction method similar to volume of fluid is applied to deal with topological change problems. A high order Level Set (LS) method is applied to evolve the free interface, with the Level Set velocities from exact Riemann solver on the cut faces. Various 1D and 2D numerical examples are tested to show the robustness and ability of the present method in wide flow variable domains. This method benefits from cut cell on the sharp interface description, shows good conservation performance, and does not have the topological change difficulty of the full cut cell method presented in Chang, Deng & Theofanous, J. Comput. Phys., 242 (2013), pp. 946–990.

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1 Introduction

During the last decades, various numerical methods have been presented to study the dynamics of compressible multi-phase flows with clear material interfaces. In Lagrangian framework, a free interface can be tracked by mesh faces so that it can be dealt with sharply. But Lagrangian schemes have difficulty when the interface deforms strongly.

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[*] Corresponding author.

Email: baixiao@csrc.ac.cn (X. Bai), xiaolong.deng@csrc.ac.cn (X. L. Deng)

In Eulerian framework, a free interface needs to be captured/tracked by special methods, including Volume of Fluid [1,2], Level Set [3–6], Phase Field [7,8] method, Front Tracking [9,10], Cut Cell [11,12] et al..

In these numerical methods, how to deal with the jump conditions on the free interface is the key of getting good results. As a simple but effective way, several Ghost Fluid methods (GFMs) [13–19] have been presented. GFMs can be combined with different interface capturing/tracking methods. However, due to the existence of ghost fluid and ghost cells, the flow conservation may be not kept well near the interface, and the discontinuity position may be not captured very accurately. Hu et al. [20] presented a conservative interface method for compressible flows based on LS method, in which the concept of cut cell is applied and a mixing procedure is used to deal with small cells. Nourgaliev et al. [11] presented a cut cell method to deal with incompressible interfacial instabilities. Chang et al. [12] presented a consistent, conservative, all-speed sharp interfacial method, in which curved cut faces and unstructured mesh are generated by a cut cell scheme, and a merging scheme is applied to eliminate very small cells. With the realization of cut cell and curved cut faces, high accuracy is achieved, jump conditions are fully satisfied, and high density/pressure/viscosity ratio, strong surface tension, and strong acoustic-impedance mismatch can be handled naturally. However, topological change cannot be dealt with yet in this scheme due to the difficulty of handling multi-cut in one cell.

In this paper, we are considering the two-phase flow problems governed by the Euler equations. A real-ghost mixing method is presented, which helps to deal with the small cells cut by the cut faces, and makes the reconstruction and value update on the cells passed by the interface uniformly with the regular cells. A cut face reconstruction similar to volume of fluid is applied to solve the topological change difficulty of the full cut cell method presented in Chang et al. [12]. Together with the straight-line cutting method, high order LS method, and GFMs, a new sharp interface method is realized. Various 1D and 2D test cases show that this method can be widely applied in the compressible multi-phase problems with or without topological change accurately and robustly.

The remainder of this paper is organized as follows. In Section 2, a detailed description of the numerical implementation of the method is given. In Section 3, a set of numerical examples are presented to illustrate the feasibility and robustness of the proposed method. Finally, concluding remarks are given in Section 4.

2 Numerical methods

2.1 Infrastructure

In this work, the background mesh is structured, and some numerical schemes for unstructured mesh are applied near the material interface, around which cut cells and ghost cells are generated. Finite volume method is applied, with AUSM$^+$-up [21,22] scheme to calculate the fluxes on the regular faces, and exact Riemann solver [12,22] on the cut